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TECHNICAL NOTE

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THERMAL-STRESS FATIGUE CRACKING OF TURBINE BUCKETS OPERATED AT 1700° F IN A TURBOJET ENGINE WITH LONG PERIODS OF OPERATION BETWEEN STARTS

By Robert A. Signorelli, James R. Johnston
and William J. Waters

Lewis Research Center
Cleveland, Ohio

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SUMMARY

Four high-strength nickel-base bucket materials were tested at 1700° F in a J47 turbojet engine. The operating time between starts was increased compared with a previous investigation (TN D-125). The investigation was conducted to study the effect of increased operating time between starts on the thermal-stress fatigue resistance of the alloys tested. The bucket materials used in this test were Sel-1, B & B, forged Udimet 500, and Inconel 713.

Thermal-stress fatigue cracking occurred in some buckets of each alloy group early in the test and in 48 to 100 percent of the buckets of each alloy group at the conclusion of the test (after 33 starts and 357 hr at rated speed). Although thermal-fatigue cracking occurred early, only two buckets fractured (broke into two or more pieces) during the test. Increased operating time between starts permitted substantial increases in accumulated rated-speed operating time for all alloys before bucket cracking occurred. Compared with the previous investigation (TN D-125) increased operating time between starts decreased the number of starts to cause cracking of buckets for alloys B & B and forged Udimet 500, but not for alloys Sel-1 and Inconel 713. Increased operating time between starts also increased the number of buckets cracked for a given number of starts for alloys Sel-1, B & B, and forged Udimet 500. The mode by which bucket cracks progressed to fracture was the same as described in TN D-125. The fractures occurred by mechanical-fatigue progression of thermal-stress fatigue cracks.

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INTRODUCTION

Thermal-stress fatigue cracking has been observed in turbine buckets in several investigations (refs. 1 to 4). This type of failure was shown to be primarily due to thermal stresses generated during engine starts (ref. 3). In the investigation of reference 4, five nickel-base high-temperature alloys were operated at a bucket temperature of 1700° F in a turbojet engine to determine both the thermal-fatigue crack resistance of these alloys and the mechanism by which cracks progressed to complete fracture. Due to the high test temperature, engine operation had to be repeatedly interrupted for engine maintenance, which resulted in frequent starts (short periods of operating time between starts). Thermal-stress fatigue cracking occurred in buckets of all alloy groups shortly after the tests were initiated, and at the conclusion of the test, after 49 starts and 70 hours, from 60 to 90 percent of the buckets in each alloy group were cracked. This high incidence of thermal-stress fatigue cracks was primarily attributed to the frequent engine starts encountered.

It was also shown in a previous investigation (ref. 3) that rated-speed operation between engine starts markedly reduced the number of starts necessary to cause cracking of the bucket materials investigated, S-816 and M-252. Specifically, the number of starts necessary to initiate cracking was reduced by a factor of 2 for M-252 and 4 for S-816 with 15 minutes of rated-speed operation between starts compared with no time at rated between starts. Of course the investigation of reference 3 was conducted with a lower maximum bucket temperature (1500° F) and different bucket materials than those used in reference 4. Nevertheless, it was believed that the results were indicative of a basic trend and that increasing the time of 1700° F engine operation between starts would further reduce the thermal-stress fatigue crack resistance (i.e., number of starts to cause cracking) that was demonstrated by the alloys investigated in reference 4.

The present investigation was therefore conducted to continue the study of bucket thermal-stress fatigue cracking in a J47 engine operated at 1700° F, but with increased time of rated-speed operation between engine starts. In particular, the study was concerned with: (1) the number of starts to cause at least one bucket to crack in each alloy group, (2) the number of buckets cracked after a given number of starts, and (3) the mode and rate of progression of cracks. The engine was operated for repeated cycles of 15 minutes at rated speed and 5 minutes at idle speed. This is identical to the operating cycle used in the investigation of reference 4, but in the present study the engine was modified to permit increased operating time between starts compared with reference 4. The buckets tested were of alloys Sel-1, B & B, forged Udimet 500, and Inconel 713, four of the five materials tested in reference 4. Bucket elongation measurements, surface and metallographic examinations of failed buckets, and stress-rupture tests of specimens cut from untested buckets were also made.

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MATERIALS, APPARATUS, AND PROCEDURE

Bucket Materials

Investment cast buckets of alloys Sel-1, B & B, and Inconel 713 and forged buckets of Udimet 500 from the same lots used in reference 4 were evaluated in this engine test. Although the intention was to evaluate all five alloys used in the previous investigation (ref. 4), sufficient buckets of cast Udimet 500 were not available. Typical chemical compositions of the alloys are shown in table I. The number of buckets of each alloy group engine tested and the heat treatment applied to each alloy group by the supplier are shown in table II. Sel-1, B & B, and forged Udimet 500 buckets were tested in the as-heat-treated condition. Inconel 713 buckets were engine operated in the as-cast condition. The number of B & B buckets tested was small compared with other alloy groups. However, alloy groups containing about this number of buckets have been used in previous engine investigations and were considered sufficiently large to provide data representative of the alloys. All test buckets were inspected before engine testing using radiographic and fluorescent dye penetrant methods. Test buckets were required to be free of defects detectable by X-ray radiography but were allowed to contain some small surface defects detectable with fluorescent dye inspection in the central portion of the airfoil and in the base.

Engine Modifications for 1700° F Operation

The engine used in this investigation was modified for 1700° F operation (buckets at 1700° F) as described in reference 4. Basically the modifications consisted of cooling the turbine stator blades and supplying additional cooling air for the turbine disk. Also, operation of the fuel regulator was altered to permit higher fuel flow at rated-speed conditions. Additional modifications were required for this investigation in order to minimize interruption of the test cycle for maintenance and repairs. The two components contributing most to the frequent shutdowns encountered in the investigation of reference 4 were the sheet-metal shroud band surrounding the rotating buckets and the exhaust cone. Customarily, a thin shroud band of 0.040-inch Inconel sheet was installed as part of the engine casing in turbojet engines used for bucket material investigations. This was done to permit fragments of failed buckets to escape readily from the engine by tearing through the band, and thus minimize impact damage to other buckets. During operation at a 1700° F bucket temperature, this thin sheet metal tended to overheat, warp, and burn through. Air cooling the shroud band greatly reduced the severity of this problem. A ring of jets was provided to direct the cooling air supplied from an auxiliary air source.

The exhaust-cone repair frequency was reduced by substituting heavier gage (0.078 in.) Inconel sheet for the standard gage (0.040 in.) stainless steel normally used. Also the diameter of the base of the inner exhaust cone was reduced to avoid overheating the downstream face of the turbine disk. Previously, warping of the standard inner exhaust cone caused the edge to project into the hot gas stream and divert a stream of hot gases into the cone and against the turbine disk. With the diameter of the base of the heavier gage cone reduced, the warpage could be tolerated because the cone edge did not project into the hot gas stream. In addition to these modifications, the number of starts was further reduced by operating the test engine on a three-shift basis. This procedure eliminated the routine shutdowns at the end of each work day. These modifications reduced the frequency of stops by a factor of 8 compared with the previous investigation (ref. 4).

Stress and Temperature Distributions in Buckets

The centrifugal stress and temperature distributions in bucket airfoils at rated-speed and advanced-temperature conditions are shown in figure 1. The centrifugal stress was calculated, by the method of reference 5, using the bucket geometry, material density, and engine rotational speed.

The temperature distribution shown in figure 1 was obtained before the actual bucket investigation was initiated. To do this, the engine was first operated with U. S. Air Force stock S-816 alloy buckets for sufficient time to obtain equilibrium conditions at rated speed and 1700° F. Temperature measurements were then obtained from thermocouples imbedded in four turbine buckets.

Engine Operation

A turbine wheel containing 81 test buckets, two shortened thermocoupled S-816 buckets, and rejected buckets from the investigation of reference 4 was operated in this test. The rejected buckets had been found unsatisfactory in surface and radiographic inspections but were used of necessity to make up the complement of 96 buckets. The turbine wheel was installed in a J47-25 engine modified as previously described and operated for repeated cycles of 15 minutes at rated speed (7950 rpm) with a 1700° F bucket temperature and about 5 minutes at idle speed (3000 rpm). Engine operation was continuous except for stops necessary for maintenance and repairs.

Bucket stress and temperature were maintained at the previously measured conditions shown in figure 1, by adjusting the engine speed and exhaust-nozzle area, respectively. Bucket temperatures were monitored during the tests by means of thermocouples imbedded at the normal midspan position in each of two S-816 alloy buckets that were included as part of the complement of turbine buckets tested. Since S-816 alloy buckets do not have sufficient strength to operate for more than 20 hours at 1700° F in a J47 engine, a 5/8-inch section was cut from the tip of the airfoil to reduce centrifugal stresses to an acceptable level. Unpublished NASA data had indicated that shortening the buckets by this amount did not measurably change the temperature distribution at the normal midspan position. Thermocouple temperature signals were transmitted through slip-rings to a recording potentiometer in a manner similar to that described in reference 6.

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Bucket Elongation Measurements

Two buckets of each alloy group were scribed near the trailing edge at 1/2-inch intervals, as shown in figure 2. Bucket elongation measurements were made after some necessary shutdowns and at the conclusion of the test. Since the investigation demanded that the engine be operated with as few starts as possible, the engine was never stopped for the sole purpose of bucket inspection. The measurements were made using an optical micrometer having a sensitivity of 0.0001 inch. However, elongation data were influenced by distortion of the buckets and by human error and were therefore considered to be reproducible only to ±0.001 inch or ±0.2 percent elongation in each 1/2-inch gage length.

Surface Examination of Buckets

Buckets were examined for cracks using fluorescent dye penetrant inspection during necessary shutdowns. Inspections were made at least after every five engine starts or after 40 hours at rated speed. The number of buckets of each alloy group with thermal-stress fatigue cracks was recorded at each inspection. Cracked buckets were considered failed, but were reinserted in the engine for further testing along with uncracked buckets to permit study of the progression of cracks to fracture.

Metallographic Studies

Two tested buckets with representative thermal-stress fatigue cracks were taken from each alloy group and sectioned for metallographic examination. Photomicrographs were taken to illustrate typical failed surfaces. An area near the leading edge at the midspan was also examined to determine the general microstructure. Since the buckets were from the same lots as those used in the investigation of reference 4, representative metallographic specimens from untested buckets were already available for examination.

Stress-Rupture Tests

Stress-rupture properties of each alloy group were determined from specimens cut from airfoils of untested buckets. The type and size of the specimens and the region of the bucket from which each was machined are shown in figure 3. Rupture tests were performed in air at 1700° F over a range of stresses.

RESULTS AND DISCUSSION

Bucket Failure

Thermal-stress fatigue cracking occurred in buckets of all alloy groups. As observed in previous investigations (refs. 1 to 4), these cracks were small and occurred over a considerable length of the bucket leading edge. Typical cracked buckets are shown in figure 4. Bucket failure data are plotted against number of starts in figure 5, since this has been shown (ref. 3) to be the primary cause of thermal-stress fatigue cracking in this engine. The position of each data point indicates the number of starts after which cracks were first observed in each bucket. A nonlinear time scale, showing the hours at rated speed accumulated at each inspection, is also provided for convenience. The figure indicates that no cracking was found after 8 starts and 83 hours at rated speed; however, cracking was noted simultaneously in buckets of all alloy groups after 13 starts and 117 hours at rated speed. More than 50 percent of the buckets of alloys B & B and forged Udimet 500 were cracked at that time. Only four additional starts (total of 17) were necessary to crack more than 50 percent of the buckets of alloy Sel-1. Inconel 713 buckets had a much lower percentage of buckets cracked after a given number of starts. At the conclusion of the test (33 starts and 357 hr at rated speed) from 48 to 100 percent of the buckets in each alloy group had cracked.

Only two buckets, both Sel-1 alloy, fractured during the entire test. Fracture occurred by mechanical-fatigue progression of thermal-stress fatigue cracks. Both of the fractured buckets were initially cracked after 17 starts and 164 hours at rated speed and fractured after 26 and 33 starts (314 and 357 hr at rated speed), respectively.

The effects on bucket failure of increased operating time between starts are indicated by comparison of these data with those of the previous study (ref. 4). These data are shown in table III and figure 6. As indicated previously, buckets for both investigations were from the same lots. The average time at rated speed between starts was about 1.4 hours (49 starts in 70 hr) in the preceding study and about 11 hours (33 starts in 357 hr) in this study. Whereas some buckets from all alloy groups were cracked after 13 starts in this investigation, cracked buckets were first noted in the preceding investigation after 28 starts for alloys B & B and forged Udimet 500, after 10 starts for alloy Sel-1, and after 12 starts for alloy Inconel 713. Thus, increased time at rated speed between starts decreased the number of starts required to crack buckets of the two alloys that displayed greater resistance to cracking in the previous investigation (B & B and forged Udimet 500). Increased rated-speed operating time between starts also decreased the number of starts required to crack 50 percent of the buckets for three of the four alloy groups. Alloys B & B and forged Udimet 500 showed cracks in more than 50 percent of the buckets after 13 starts, and Sel-1 alloy had cracks in more than 50 percent of the buckets after 17 starts. The number of starts required to crack 50 percent of the buckets in the investigation of reference 4 were 45 for B & B, 36 for forged Udimet 500, and 29 for Sel-1. Inconel 713 buckets required about the same number of starts to crack 50 percent of the buckets, 33 in this investigation as against 28 starts in the earlier investigation. On the basis of these results, it appears that longer rated-speed operation between starts had a deleterious effect on thermal-stress fatigue cracking.

Determination of the variables which contributed to the decrease in thermal-fatigue resistance encountered herein with three of the four alloys is beyond the scope of this investigation. However, reduction in resistance to thermal-stress fatigue cracking of S-816 and M-252 in reference 3 was attributed to localized creep damage at the leading edge and embrittlement resulting from overaging.

Since thermal-stress fatigue cracking was primarily caused by starting, the evaluation of resistance to cracking reported herein was based on the number of starts. It should be noted however that the total operating times at which cracking occurred were also increased by increasing the operating time between starts. Thus increased bucket life, in terms of operating hours, may be obtained by decreasing the frequency of starting.

The mode by which cracks progressed to cause fracture of buckets apparently was not affected by the increased time of rated-speed operation between engine starts. The two buckets that fractured, both Sel-1, did so by mechanical-fatigue progression of a thermal-stress fatigue crack, the same mechanism encountered in previous investigations (refs. 1, 2, and 4). The two buckets were initially cracked after 164 hours at rated speed and ran an additional 150 and 193 hours, respectively, before fracture occurred.

Elongation of Buckets

Elongation measurements taken from two scribed buckets of each alloy indicated that almost negligible creep resulted from 357 hours of rated-speed and 1700° F operation for each alloy. As would be expected, the greatest elongation occurred in the zone located in the central portion of the bucket span, zone 3, which has the most severe combination of centrifugal stress and temperature. The elongation readings for all the alloys ranged from 0.3 to 0.5 percent (reproducibility ±0.2 percent).

Metallographic Studies

Photomicrographs of the general structure of buckets of each of the alloys after operation in the engine for the full 357 hours of the test are shown in figure 7. Except for a slight agglomeration of some of the smaller precipitates, the microstructures after the test were almost unchanged from the as-received condition (ref. 4).

Photomicrographs illustrating failed and fractured buckets are shown in figure 8. Figure 8(a) shows a typical crack which has not progressed sufficiently to cause fracture of the bucket. The thermal-fatigue crack appears intergranular, and is similar to the cracks obtained in earlier investigations (refs. 1 to 4). Figure 8(b) illustrates an edge of the failed surface of one of the two fractured buckets. The transition from the rough intergranular crack surface to the smooth transgranular mechanical-fatigue surface is evident. The fracture surface displayed concentric rings, which are indicative of a mechanical-fatigue failure.

Stress-Rupture Evaluations

Results of rupture tests run at 1700° F on specimens cut from bucket airfoils are shown in figure 9. Alloys Sel-1 and forged Udimet 500 both showed rupture strength of about 20,000 psi for 100-hour life. B & B alloy showed a higher strength, 23,000 psi, and Inconel 713 had the highest strength, 26,000 psi for 100-hour life.

SUMMARY OF RESULTS

The following results were obtained from an investigation in which buckets of alloys Sel-1, B & B, forged Udimet 500, and Inconel 713 were operated in a J47 engine for cycles of 15 minutes at rated speed and 5 minutes at idle speed. Bucket temperature was kept at 1700° F during rated-speed operation, and the average time of rated-speed operation between starts was increased compared with a previous investigation (TN D-125) from 1.4 to 11 hours (a factor of 8). The results obtained are compared with those of the previous investigation (TN D-125).

1. Thermal-stress fatigue cracking occurred in all alloy groups early in the test and in 48 to 100 percent of the buckets of each alloy

group at the conclusion of the test (33 starts and 357 hr). Although thermal-stress fatigue cracking occurred relatively early (13 starts, 117 hr), only two buckets fractured during the entire test.

2. Increased operating time between starts decreased the number of starts to cause cracking of buckets for alloys B & B and forged Udimet 500, but not for alloys Sel-1 and Inconel 713. In this investigation cracks were initiated in buckets of all alloys after 13 starts, whereas in the preceding study, B & B and forged Udimet 500 buckets were cracked after 28 starts and Sel-1 and Inconel 713 after 10 and 12 starts, respectively.

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3. Increased operating time between starts also increased the number of buckets cracked with a given number of starts for alloys Sel-1, B & B, and forged Udimet 500. For example, cracks were formed in 50 percent of the buckets of these alloy groups after 13 and 17 starts in this investigation, while from 29 to 45 starts were required in the preceding investigation. Cracks were formed in 50 percent of the Inconel 713 buckets after at least 33 starts as against 28 starts in the previous investigation.

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4. Increased operating time between starts permitted substantial increases in accumulated rated-speed operating time for all alloys before bucket cracking occurred.

5. The increased time of operation at 1700° F and rated speed between starts, and the longer total time compiled at rated speed in this investigation, did not change the mode by which bucket cracks progressed to fracture. The two buckets (both Sel-1) that fractured did so by mechanical-fatigue progression of a thermal-stress fatigue crack, the same mode of failure as encountered in the previous investigations. These buckets ran with cracks for 150 and 193 hours, respectively, before fracture occurred.

6. Since only two buckets fractured in 357 hours of engine operation at 1700° F, it appears that the alloy groups investigated possess considerable potential as bucket materials for advanced-temperature operation if thermal-stress fatigue failures can be minimized.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 18, 1959

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2. Springsteen, D. F., Gyorgak, C. A., and Johnston, J. R.: Origin and Development of Leading-Edge Cracks in Turbojet Engine Buckets. NACA RM E57C12, 1957.

3. Johnston, James R., Weeton, John W., and Signorelli, Robert A.: Engine Operating Conditions that Cause Thermal-Fatigue Cracks in Turbojet-Engine Buckets. NASA MEMO 4-7-59E, 1959.

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6. Farmer, J. Elmo: Relation of Nozzle-Blade and Turbine-Bucket Temperatures to Gas Temperatures in a Turbojet Engine. NACA RM E7L12, 1948.

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TABLE I. - TYPICAL CHEMICAL COMPOSITION OF ALLOYS[a]

Alloy	Fabrication	Weight percent of element								
		Ni	Co	Cr	Mo	Ti	Al	C	B	Cb
Sel-1	Vacuum cast	Bal (49)	27	15	2.5	2.25	3.75	0.1	---	-
B & B	Vacuum cast	Bal (44)	30	15	5	2.5	3	---	0.5	-
Udimet 500	Forged	Bal (55)	15	20	4	3	2.75	0.1	---	-
Inconel 713	Argon cast	Bal (76)	--	12	4	0.5	5.5	---	---	2

[a]Data supplied by vendor.

TABLE II. - NUMBER OF BUCKETS TESTED AND HEAT TREATMENTS APPLIED

Alloy	Number of buckets tested	Heat treatment
Sel-1 B & B	19 5	Solution-treat, 2050° F, 2 hr; air-cool; age, 1400° F, 16 hr; air-cool
Forged Udimet 500	28	Solution-treat, 1975° F, 2 hr; air-cool; age, 1550° F, 16 hr; air-cool; age, 1400° F, 16 hr; air-cool
Inconel 713	29	None (as cast)
Total	81	

TABLE III. - COMPARISON BETWEEN THERMAL-STRESS FATIGUE CRACKING

DATA OF PRESENT INVESTIGATION AND REFERENCE 4

Alloy	At least one bucket cracked				50 Percent of buckets cracked			
	Present investigation		Ref. 4		Present investigation		Ref. 4	
	Number of starts	Hours at rated speed	Number of starts	Hours at rated speed	Number of starts	Hours at rated speed	Number of starts	Hours at rated speed
Sel-1	13	117	10	6.5	17	164	29	35
B & B	13	117	28	30	13	117	45	56
Forged Udimet 500	13	117	28	30	13	117	36	50
Inconel 713	13	117	12	10	33	357	28	30

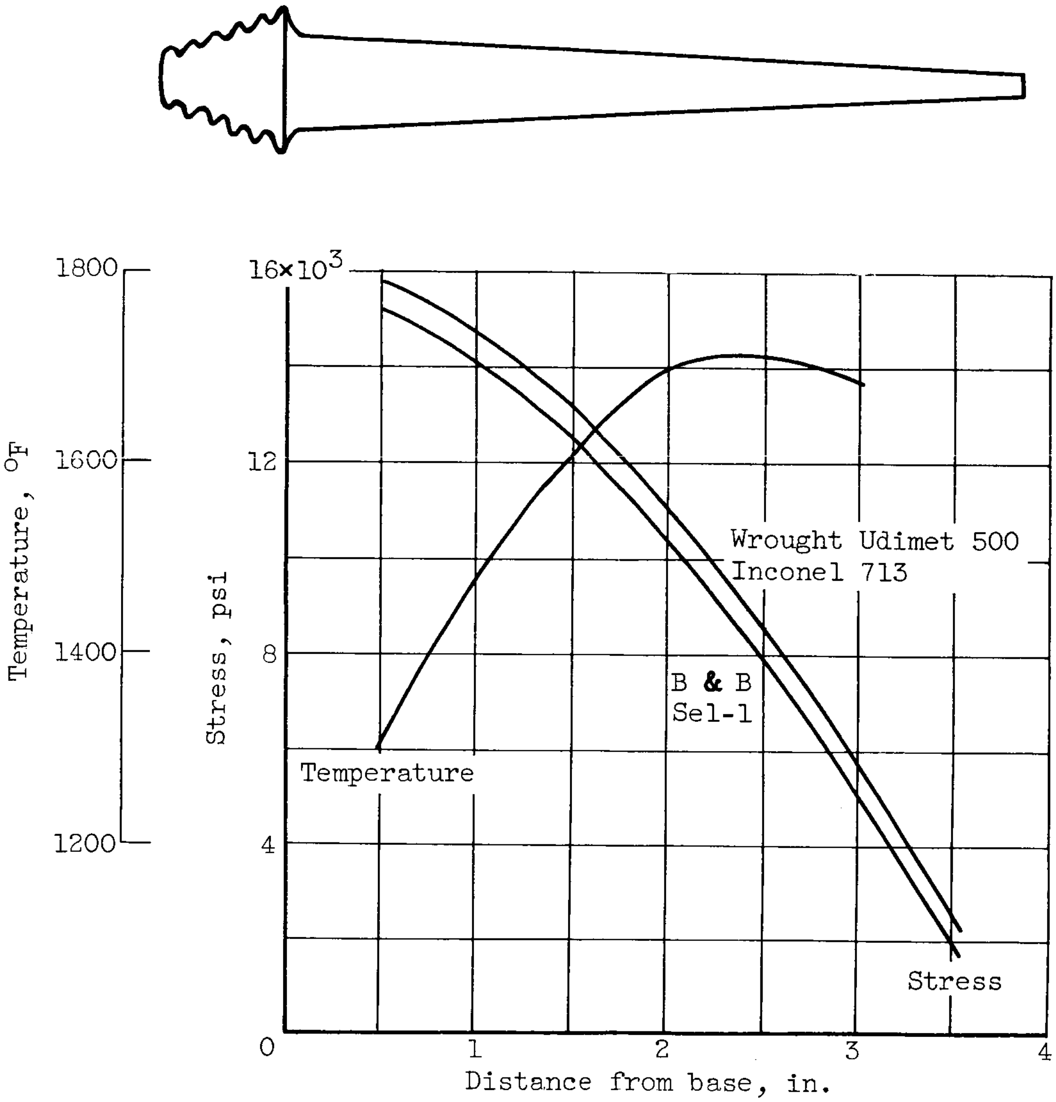

Figure 1. - Bucket stress and temperature distributions at rated conditions.

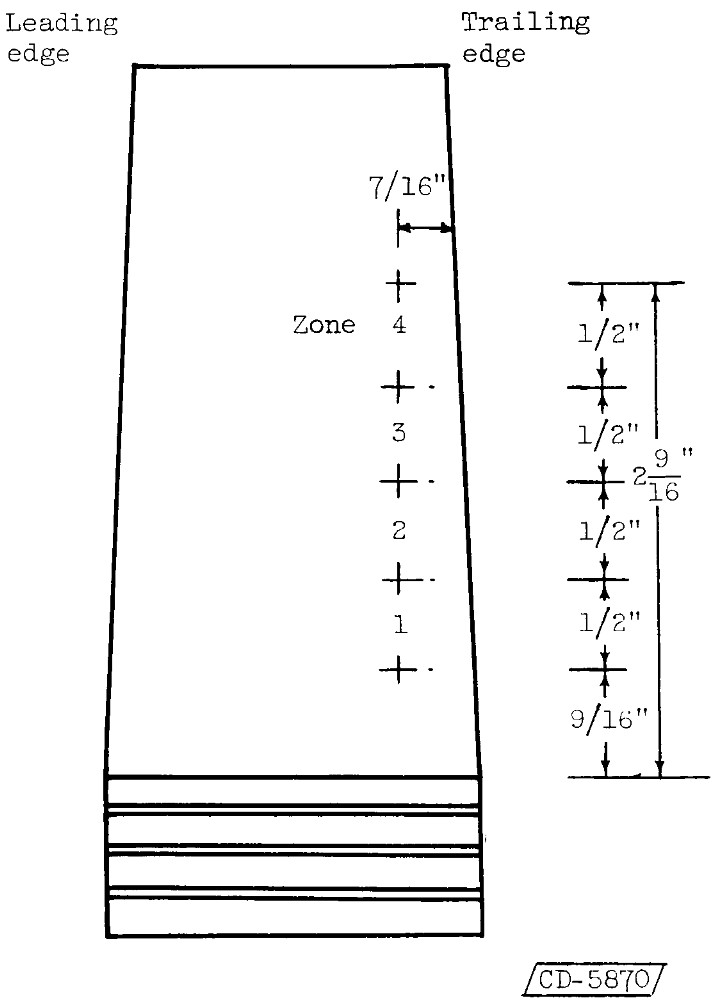

Figure 2. - Scribed bucket for elongation measurements.

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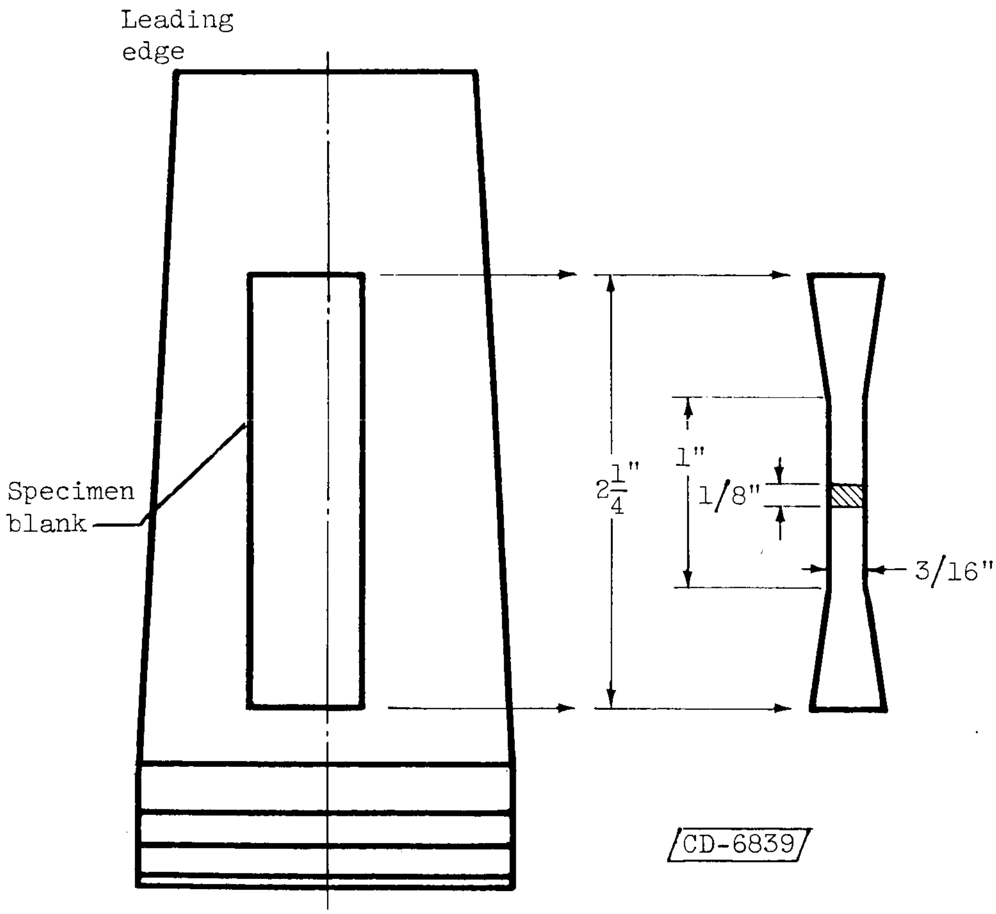

Figure 3. - Bucket airfoil stress-rupture specimen and region of bucket from which it was machined.

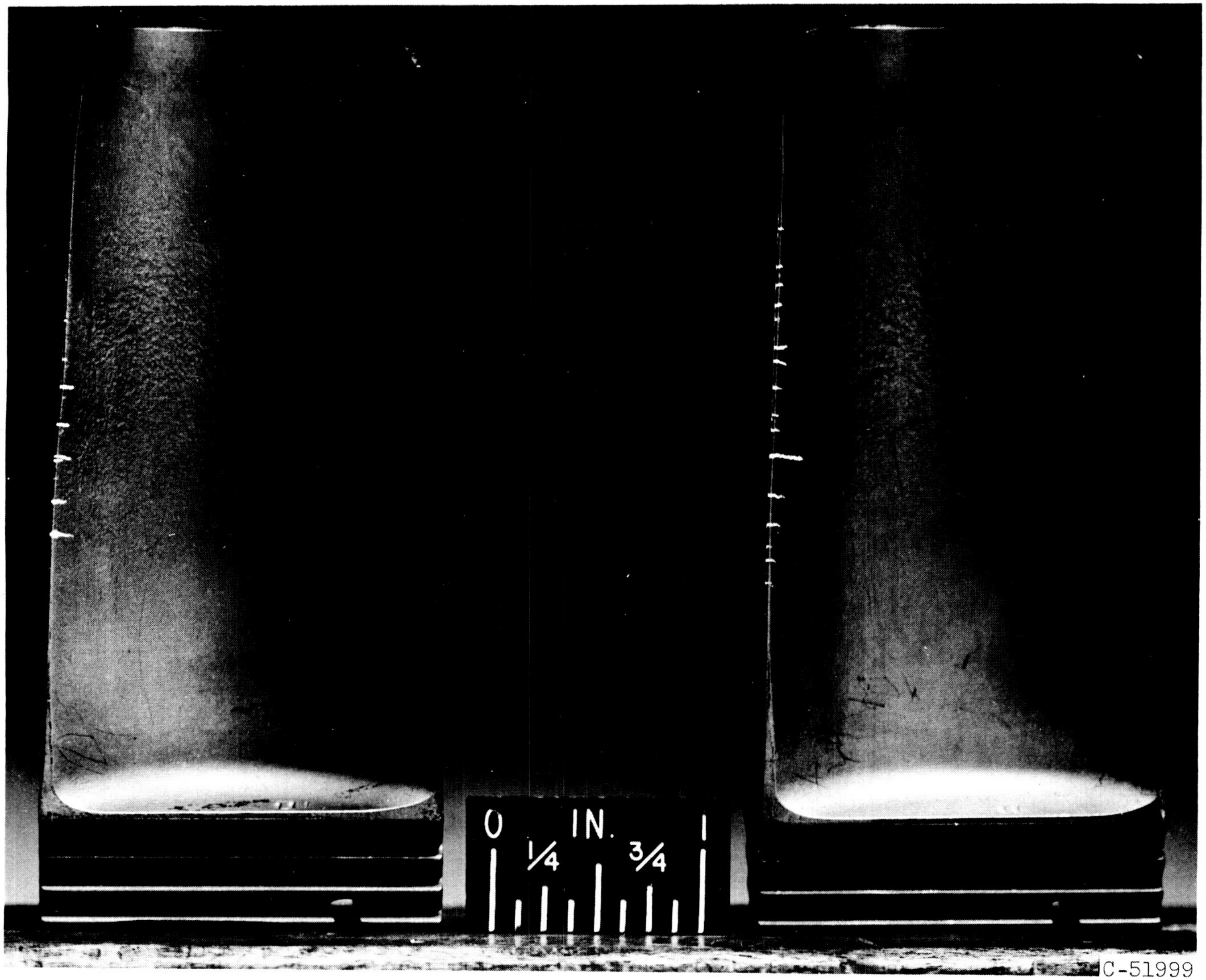

Figure 4. - Typical thermal-stress fatigue cracked buckets.

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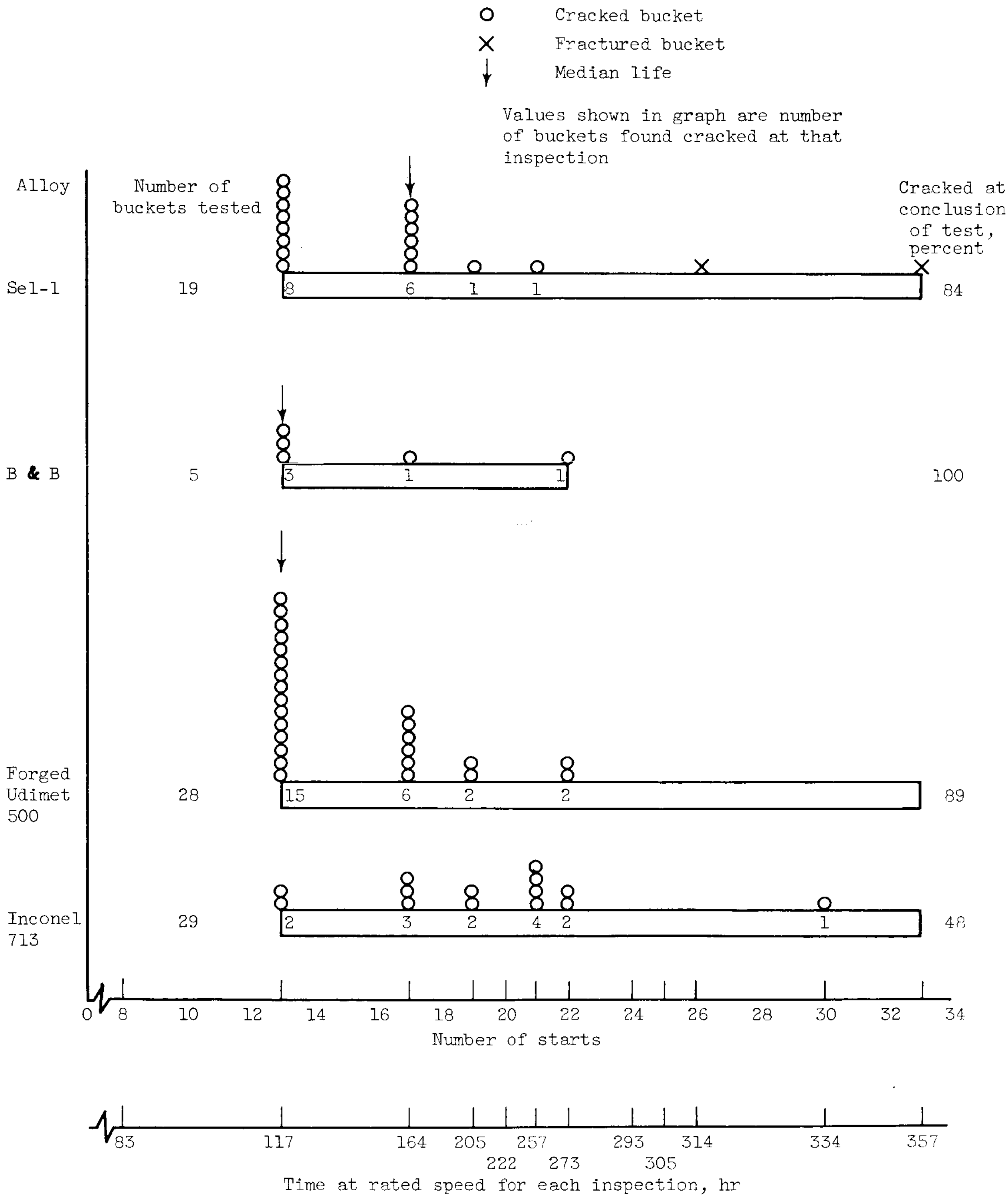
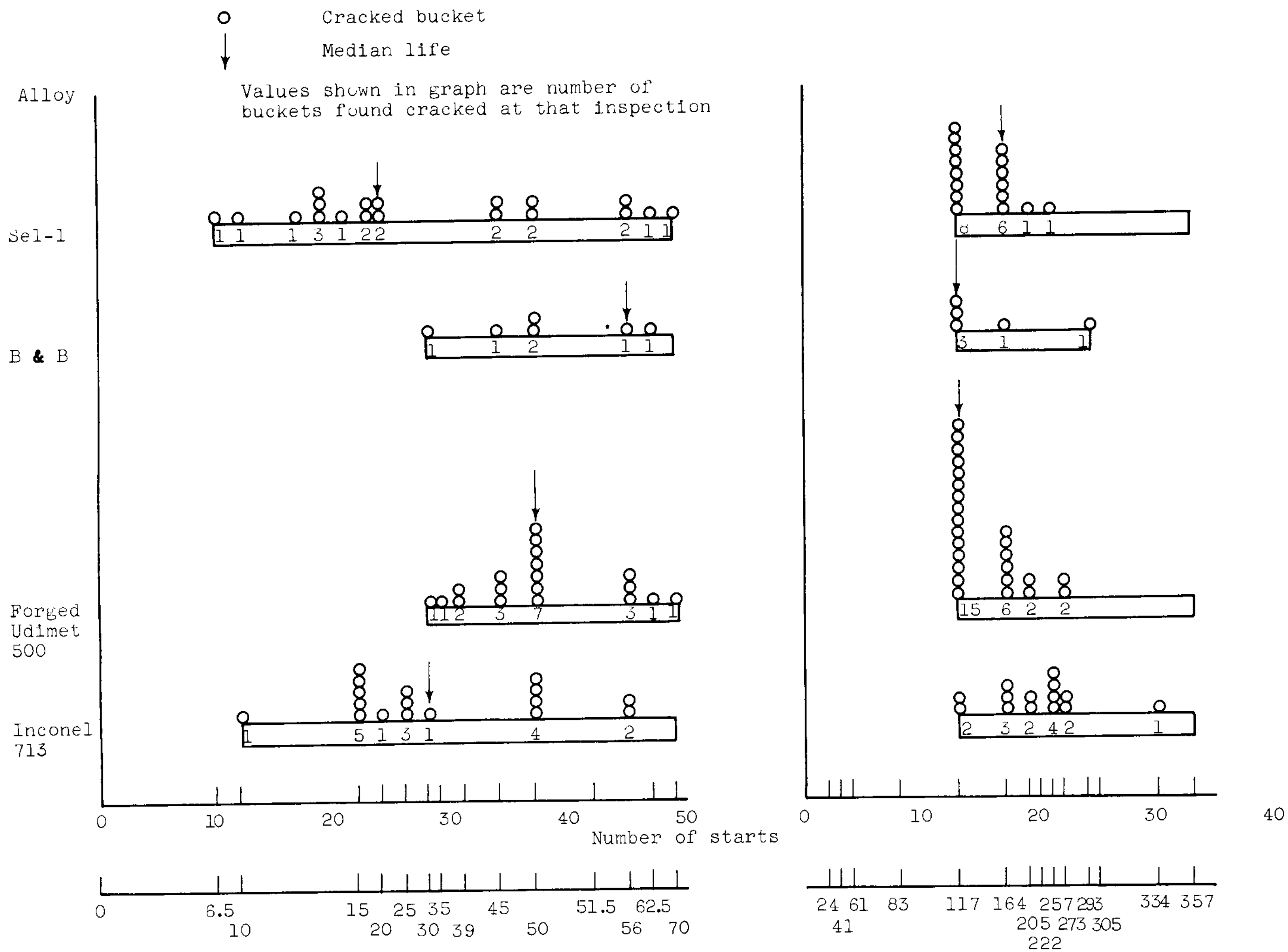


Figure 5. - Number of starts and operating hours when cracks were first found in each bucket.



(a) Reference 4.

(b) Present investigation.

Figure 6. - Comparison of thermal-stress fatigue crack data from previous investigation with data from present investigation.

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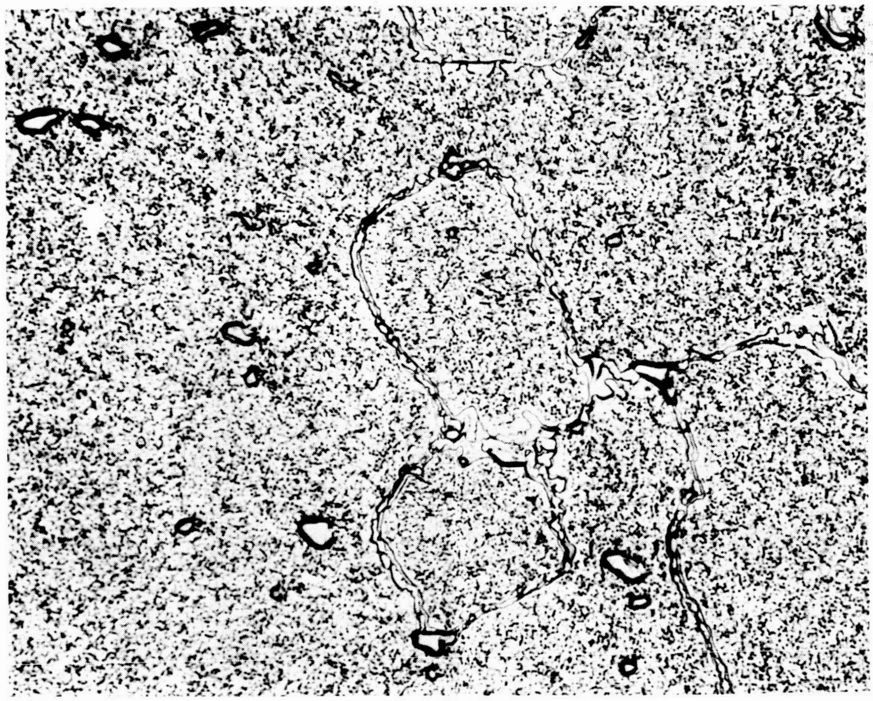
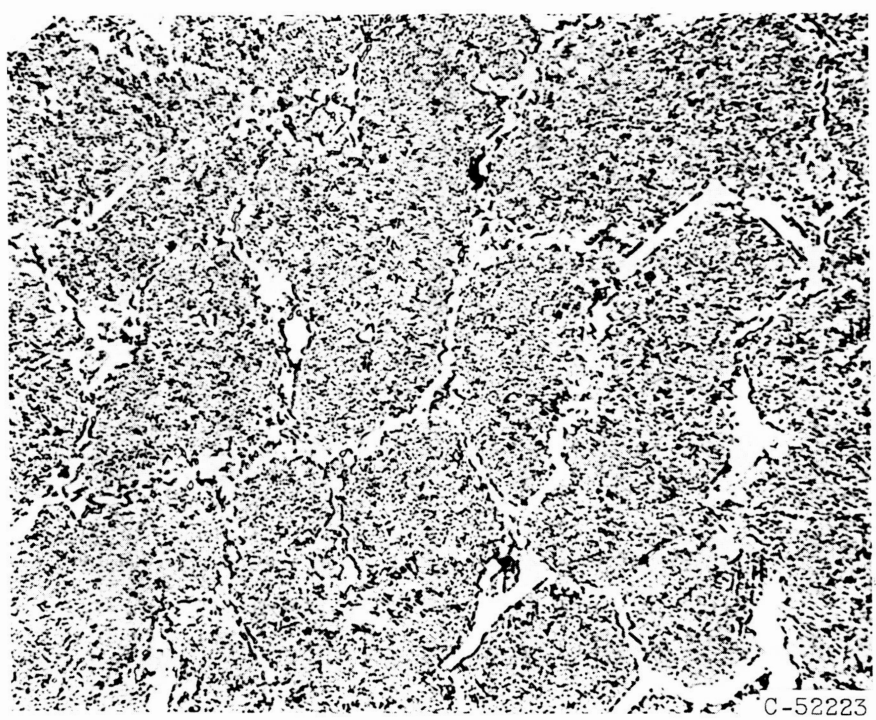
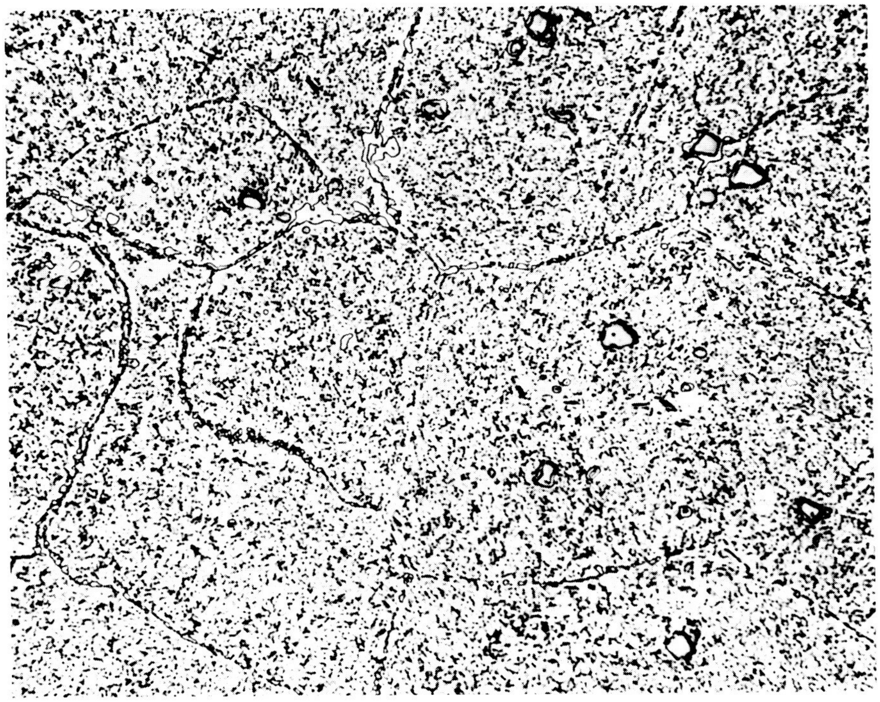


(a) Sel-1.

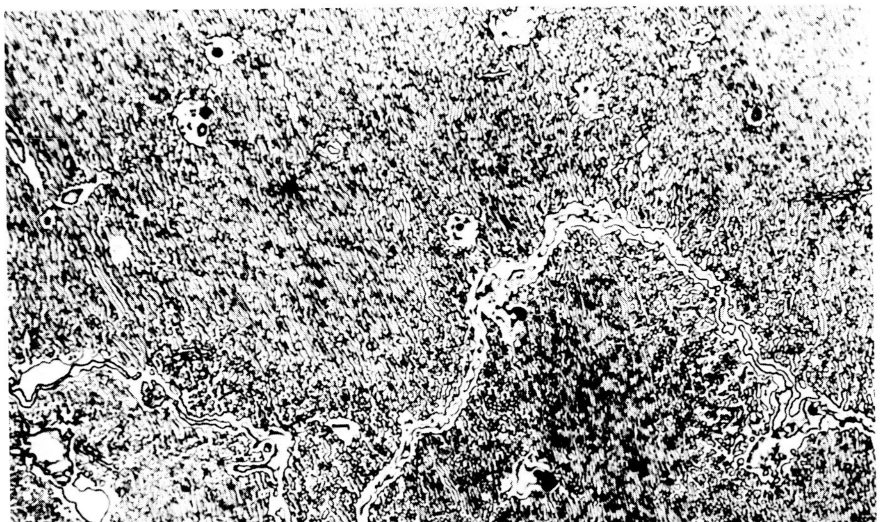


(b) B&B.

Figure 7. - Typical microstructures of engine operated buckets. Etchant: 10 percent HF, 20 percent HNO_3. X750.



(c) Forged Udimet 500.



(d) Inconel 713.

Figure 7. - Concluded. Typical microstructures of engine operated buckets. Etchant: 10 percent HF, 20 percent HNO_3. X750.

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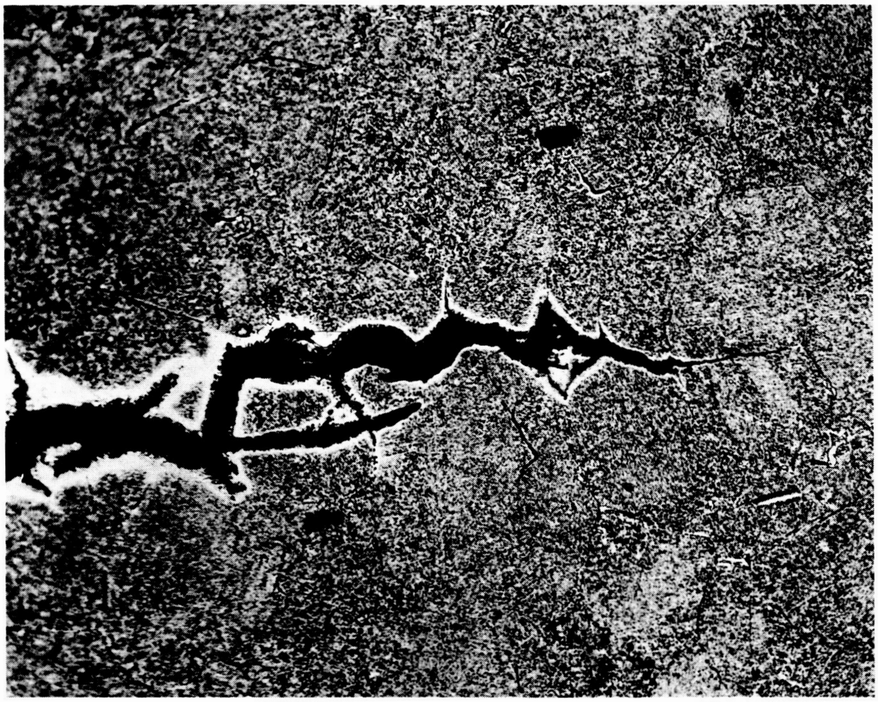
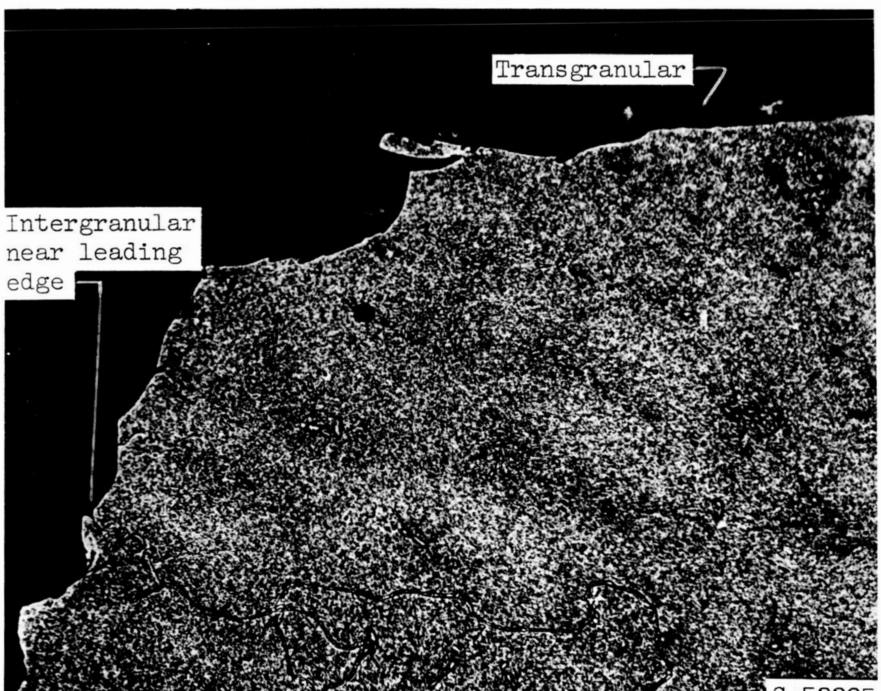


(a) Typical thermal-stress fatigue crack.



(b) Fracture that was initiated by thermal-stress fatigue and progressed by mechanical fatigue.

Figure 8. - Photomicrographs of edges of failed surfaces. Etchant: 10 percent HF, 20 percent HNO_3. X250.

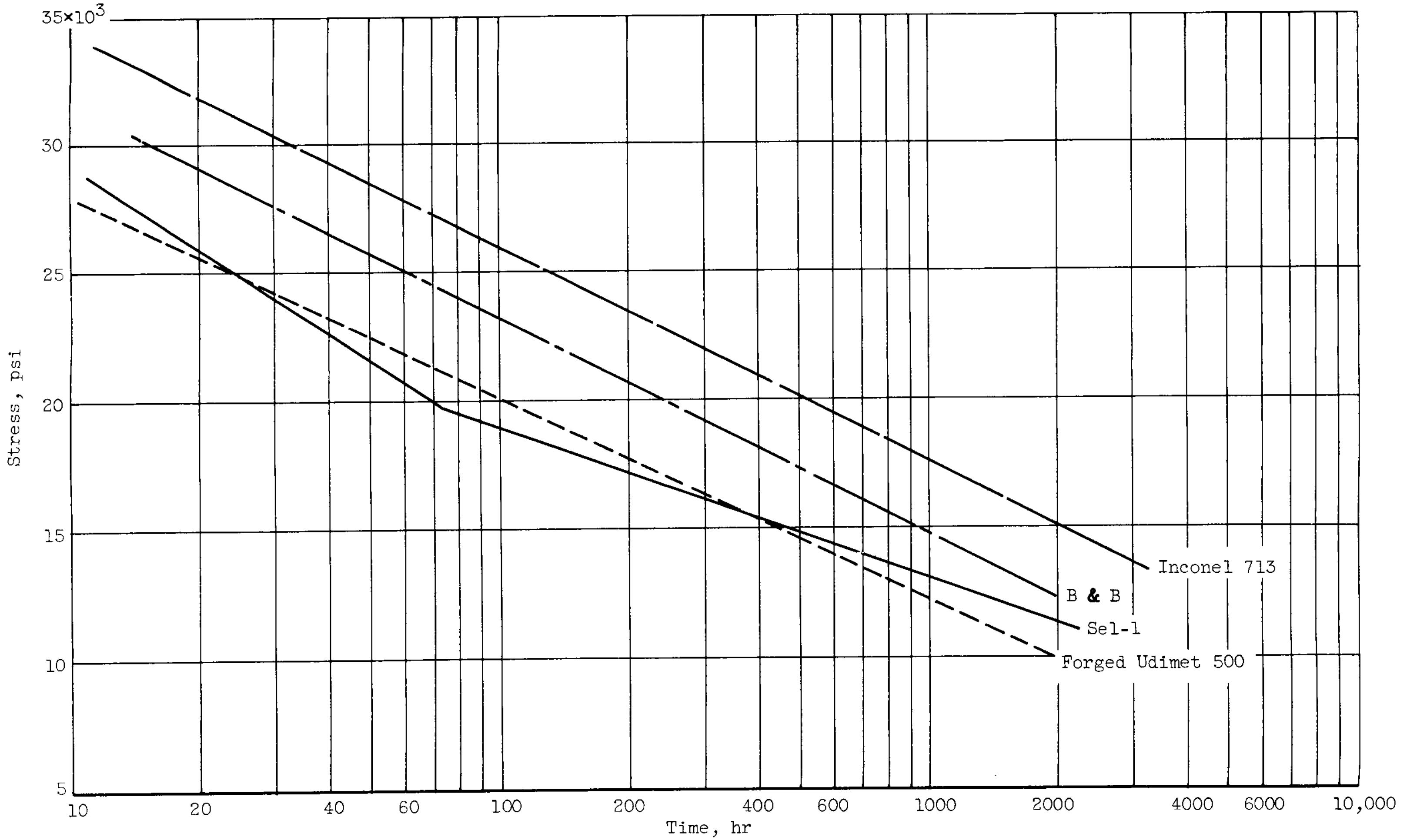


Figure 9. - Stress-rupture life of alloys at 1700° F.